

Collective motion of electrons in a strongly interacting 2D electron system

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We report the observation of strongly nonlinear $V - I$ characteristics that display two distinct thresholds and a concurrent dramatic increase in noise in the breakdown of the insulating state in a strongly interacting two dimensional electron system in silicon. With the roles of voltage and current interchanged, this behavior is strikingly similar to that observed for the depinning of the vortex lattice in Type-II superconductors. Adapting the model used for vortexes to the case of an electron solid yields good agreement with our experimental results. This strongly suggests the formation of an electron solid in the insulating phase.

Low-disorder electron systems in two dimensions (2D) are currently the focus of a great deal of attention, particularly for low electron densities where the interactions between them dominate their behavior, theoretical methods are still poorly developed, and new experimental results are of great interest. Consistent with Fermi liquid theory at high electron densities, these 2D systems are expected to form a Wigner crystal in the dilute, strongly-interacting limit [1–4]. The interaction strength is characterized by the ratio of the Coulomb energy to the Fermi energy, determined by the dimensionless parameter, $r_s = 1/(\pi n_s)^{1/2} a_B$ (here n_s is the areal density of electrons, $a_B = \epsilon \hbar^2 / m_b e^2$, and ϵ , e , and m_b are the dielectric constant, the absolute value of electron charge, and the band mass, respectively); the parameter r_s is proportional to $n_s^{-1/2}$ and increases with decreasing electron density, reaching values in excess of $r_s \gtrsim 10$ in systems investigated experimentally to date. Particularly strong many-body effects have been observed in silicon metal-oxide-semiconductor field-effect transistors (MOSFETs) [5–7]. This low-disorder 2D electron system reveals the critical behavior at low electron densities, as inferred from measurements of the effective mass [8], thermodynamic magnetization [9], and thermopower [10] in the regime of metallic conductivity. The transition to a new phase at low densities occurs at a critical density close to the density for the metal-insulator transition, which indicates the many-body origin of the insulating phase (Wigner crystal or a precursor).

Measurements of nonlinear current-voltage ($I - V$) characteristics in the zero-magnetic-field insulating phase have been previously performed in 2D electron systems in silicon MOSFETs [11, 12] and GaAs/AlGaAs heterostructures [13]. A single threshold was observed in the $I - V$ curves which has generally been attributed to the depinning of a quantum electron solid or to the breakdown of the insulating phase within a more traditional scenario such as percolation (see, *e.g.*, Ref. [6] and references therein). The observation of broad-band noise at the threshold $I - V$ curves [11, 12, 14] has not provided information that allows a choice between the two mech-

anisms. Neither has the re-entrant behavior of the insulating phase in a perpendicular magnetic field, although this could easily be interpreted as a manifestation of the competition between the Wigner crystal and the integer of fractional quantum Hall effect [15–24]. Although data in the insulating phase have generally been interpreted assuming the presence of a pinned Wigner crystal (some doubts in this interpretation have been expressed in Ref. [25]), no experimental results have provided firm evidence for the formation of a Wigner solid.

In this Letter we report the observation of strongly nonlinear $V - I$ characteristics that display two distinct threshold voltages and a concurrent dramatic increase in noise in the insulating state breakdown of a strongly interacting 2D electron system in silicon. With increasing applied voltage, the current is near zero up to a voltage threshold V_{th1} , then increases sharply until a second threshold voltage V_{th2} is reached, above which the $V - I$ characteristic is linear. In the form of fluctuations with time, the noise increases dramatically above V_{th1} , and essentially disappears above V_{th2} . The double threshold and strong noise observed in the range between them are very similar to the features that have been observed for the depinning of the vortex lattice in Type-II superconductors (see, *e.g.*, Ref. [26]) provided the voltage and current axes are interchanged. This strongly suggests collective motion of the 2D electrons after the breakdown of the insulating state. We emphasize that rather than being an ideal Wigner crystal, the 2D electron system under study is likely to be closer to an amorphous solid, which is similar to the case of the vortex lattice in Type-II superconductors where the collective pinning was observed.

Measurements were made in an Oxford dilution refrigerator with a base temperature of ≈ 50 mK on (100)-silicon MOSFETs with a peak electron mobility close to $3 \text{ m}^2/\text{Vs}$ at $T < 0.1$ K similar to those described in detail in Ref. [27]. The electron density was controlled by applying a positive dc voltage to the gate relative to the contacts; the oxide thickness was 150 nm. Samples had a Hall bar geometry of width $50 \mu\text{m}$. In contrast to previous studies, in which current was passed through the sample and the voltage between potential probes was

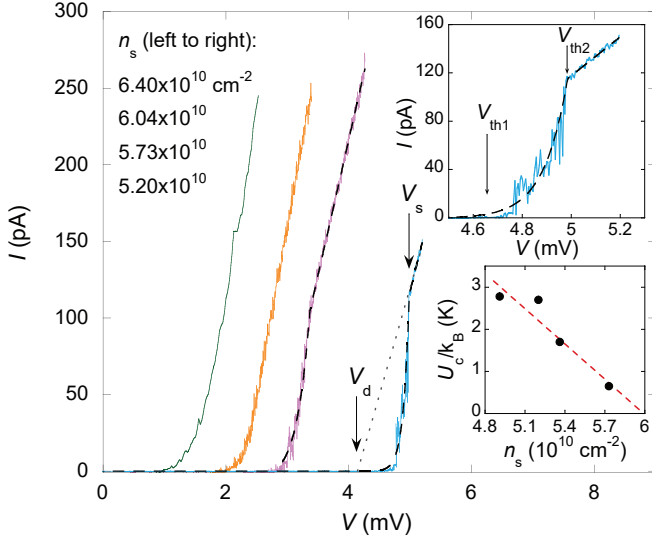


FIG. 1: Voltage-current characteristics for different electron densities in the insulating state at a temperature of 60 mK. The dashed lines are fits to the data using Eq. (5); the dynamic and static thresholds are indicated. The top inset shows the $V - I$ curve for $n_s = 5.20 \times 10^{10} \text{ cm}^{-2}$ on an expanded scale; the threshold voltages V_{th1} and V_{th2} are indicated. Bottom inset: activation energy U_c vs. electron density. The dashed line is a linear fit.

measured, here we applied dc voltage between source and drain and measured the induced current. To overcome the main experimental obstacle in the low-density low-temperature limit — high contact resistance — thin gaps were introduced in the gate metallization that allow a high electron density to be maintained near the contacts regardless of the density in the main part of the sample. As a result, contact resistances did not exceed $\sim 10 \text{ k}\Omega$ and could be disregarded in the insulating state. Measurements of the $V - I$ characteristics and noise were obtained in the main part of the sample with length $180 \mu\text{m}$. The dc current and noise were measured using a current-voltage converter connected to a digital voltmeter or lock-in.

Figure 1 shows a set of low-temperature $V - I$ curves at different electron densities in the insulating regime $n_s < n_c$ (the critical density for the metal-insulator transition $n_c \approx 8 \times 10^{10} \text{ cm}^{-2}$ in this electron system). Two threshold voltages are observed at low densities. Above an onset, V_{th1} , the current increases sharply with voltage up to a second threshold, V_{th2} , above which the slope of the $V - I$ curve is significantly reduced and the behavior is linear (see also the top inset to Fig. 1). As the electron density is increased, the value of V_{th1} decreases while the second threshold becomes less pronounced and eventually disappears. Interestingly, at $V > V_{th2}$, the $V - I$ curves are parallel to each other (i.e., the differential conductances are almost independent of density). Note that the observed behavior is quite distinct from that reported in

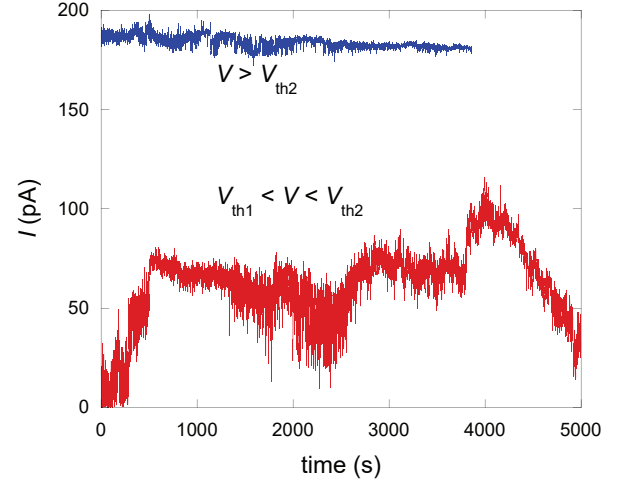


FIG. 2: The current as a function of time measured for $n_s = 5.2 \times 10^{10} \text{ cm}^{-2}$ and $T = 60 \text{ mK}$ at voltages $V = 4.90 \text{ mV}$ (lower curve) and $V = 5.44 \text{ mV}$.

the insulating state in amorphous InO films, where the current was found to jump at the threshold voltage by as much as five orders of magnitude and the $V - I$ curves exhibit hysteresis consistent with bistability and electron overheating [28, 29]. It is important to note that in our experiment the power dissipated near the onset V_{th1} is less than 10^{-16} W , which is clearly too low to cause significant electron overheating; for comparison, the power dissipated near the threshold voltage in Ref. [28] is more than three orders of magnitude higher.

In the regime in which both thresholds are present, the current measured at voltages between V_{th1} and V_{th2} exhibits strong fluctuations with time that are comparable to its value. Above the second threshold, V_{th2} , these anomalously large fluctuations disappear and the noise is barely perceptible. This is shown explicitly in Fig. 2, where the current is plotted as a function of time measured for density $n_s = 5.2 \times 10^{10} \text{ cm}^{-2}$. At fixed V in the range between V_{th1} and V_{th2} , the current fluctuates strongly with time, while these fluctuations are suppressed for $V > V_{th2}$.

Figure 3(a) shows the $V - I$ characteristics for $n_s = 5.36 \times 10^{10} \text{ cm}^{-2}$ at different temperatures. As the temperature, T , is increased, the second threshold V_{th2} becomes less pronounced and the threshold behavior of the $V - I$ curves eventually smears out due to the shrinkage of the zero-current interval.

The measured broad-band noise is shown as a function of voltage in Fig. 3(b) for different temperatures at electron density $n_s = 5.36 \times 10^{10} \text{ cm}^{-2}$. A large peak in the noise is observed between the thresholds V_{th1} and V_{th2} at the lowest temperature. This peak decays rapidly with increasing temperature, in agreement with the threshold behavior of the $V - I$ curves of Fig. 3(a). The spectrum of the generated noise, measured at its peak, is displayed in

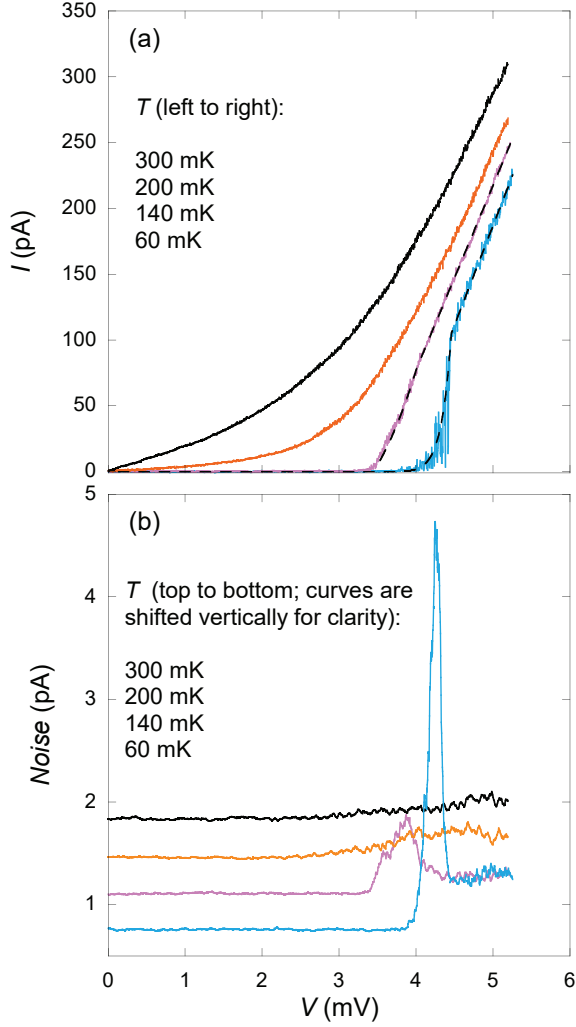


FIG. 3: (a) $V - I$ characteristics at $n_s = 5.36 \times 10^{10} \text{ cm}^{-2}$ for different temperatures. The dashed lines are fits to the data using Eq. (5). (b) The broad-band noise as a function of voltage for the same electron density and temperatures.

Fig. 4. The noise increases with decreasing frequency, f , according to the $1/f^\alpha$ law (where $\alpha \approx 0.6$) and saturates at low frequencies.

There is a striking similarity between the double-threshold $V - I$ dependence in the insulating state of Si MOSFETs and those (with the voltage and current axes interchanged) known for the depinning of the vortex lattice in Type-II superconductors (see, *e.g.*, Ref. [26]). The physics of the vortex lattice in Type-II superconductors, in which the existence of two thresholds is well known, can be adapted for the case of an electron solid. The transient region between the dynamic (V_d) and static (V_s) thresholds corresponds to the collective pinning of the solid. In this region the pinning occurs at the centers with different energies and the current is thermally activated:

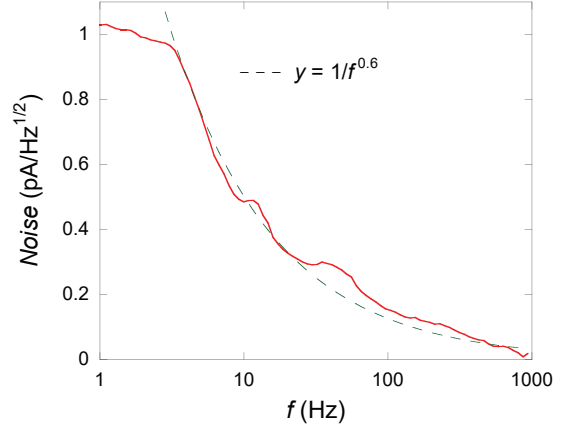


FIG. 4: Noise as a function of frequency at $n_s = 5.36 \times 10^{10} \text{ cm}^{-2}$, $T = 60 \text{ mK}$, and $V = 4.26 \text{ mV}$. The broad maxima at $f \sim 10$ and 60 Hz on the order of $10^{-1} \text{ pA}/\sqrt{\text{Hz}}$ are within the experimental uncertainty. The dashed line shows the $1/f^{0.6}$ dependence.

$$I \propto \exp \left[-\frac{U(V)}{k_B T} \right], \quad (1)$$

where $U(V)$ is the activation energy. The static threshold $V_s = V_{\text{th2}}$ signals the onset of the regime of solid motion with friction. This corresponds to the condition

$$eEL = U_c, \quad (2)$$

where E is the electric field and L is the characteristic distance between the pinning centers with maximal activation energy U_c . From the balance of the electric, pinning, and friction forces in the regime of solid motion with friction, one expects a linear $V - I$ characteristic that is offset by the threshold V_d corresponding to the pinning force

$$I = \sigma_0(V - V_d), \quad (3)$$

where σ_0 is a coefficient. Assuming that the activation energy for the Wigner solid is equal to

$$U(V) = U_c - eEL = U_c(1 - V/V_s), \quad (4)$$

we obtain the expression for the current

$$I = \begin{cases} \sigma_0(V - V_d) & \text{if } V > V_s \\ \sigma_0(V - V_d) \exp \left[-\frac{U_c(1 - V/V_s)}{k_B T} \right] & \text{if } V \leq V_s. \end{cases} \quad (5)$$

The fits to the data using Eq. (5) are shown by dashed lines in Figs. 1 and 3. As seen from the figures, the experimental two-threshold $V - I$ characteristics are described well by Eq. (5). The value of U_c decreases approximately linearly with electron density and tends to zero at $n_s \approx 6 \times 10^{10} \text{ cm}^{-2}$ (the bottom inset to Fig. 1).

This is in contrast to the vanishing at n_c of the activation energy of electron-hole pairs obtained by measurements of the resistance at currents $I \rightarrow 0$ [30]. Presumably, the vanishing U_c is related to the minimum number of the strong pinning centers for which the collective pinning is still possible. The fact that the coefficient σ_0 is approximately constant ($\sigma_0 \approx 1.6 \times 10^{-7} \text{ Ohm}^{-1}$) indicates that the solid motion with friction is controlled by weak pinning centers [26]. Thus, the physics of the vortex lattice, adapted for the case of electron solid, is relevant for the insulating state in a 2D electron system in silicon.

One can estimate the characteristic frequency of the generated noise $f \sim v_d/L$, where v_d is the drift velocity. Using the parameters corresponding to the data shown in Fig. 3(a) ($V_s \simeq 4.46 \text{ mV}$, $U_c/k_B \simeq 1.7 \text{ K}$, $I \sim 20 \text{ pA}$, $n_s = 5.36 \times 10^{10} \text{ cm}^{-2}$, and $L \sim 10^{-3} \text{ cm}$), one obtains $f \sim 500 \text{ Hz}$, which is in reasonable agreement with the experiment.

In summary, we have observed two thresholds in the low-temperature voltage-current characteristics in the insulating state in a 2D electron system in silicon, indicating that there are three distinct regions with different mechanisms for the conductivity. With increasing applied voltage, the current is near zero up to the first voltage threshold. In the voltage range between the first and second threshold, a sharp increase of the current with voltage is accompanied by dramatic fluctuations of the current with time, while above the second threshold, both the slope of the $V - I$ curves and the noise drop substantially. The striking resemblance between the behavior of the $V - I$ characteristics in the insulating state in a 2D electron system in silicon and that of the $I - V$ characteristics for the depinning of the vortex lattice in Type-II superconductors suggests collective motion of 2D electrons after the breakdown of the insulating state. Rather than being an ideal Wigner crystal, the 2D electron system under study is likely to be closer to an amorphous solid, which is similar to the case of the vortex lattice in Type-II superconductors where the collective pinning was observed.

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